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Symmetry degeneration and room temperature ferroelectricity in ion irradiated SrTiO3

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Abstract

Polar phonon modes associated with room temperature ferroelectricity are observed in $SrTiO_3$ single crystals irradiated with Ti ions. Quantitative strain analysis reveals that irradiation-induced out-of-plane strain drives the centrosymmetric cubic $SrTiO_3$ to a tetragonal-like structure in the maximum damaged region. Energy transfer from ions to electrons during ion irradiation yields defects in $SrTiO_3$ that also plays an important role for the room temperature ferroelectricity. Different from thin film techniques, the ferroelectricity in the ion irradiated $SrTiO_3$ can occur for much larger thicknesses, depending on the energy and type of ion.

1. Introduction

Bulk $SrTiO_3$ has a centrosymmetric cubic structure at room temperature, and there is a cubic to tetragonal structural transition at 105 K [1]. The dielectric constant of $SrTiO_3$ deviates from the classical Curie–Weiss law at low temperature, and it increases rapidly (up to 1.8×10^4 at 1.4 K) as the temperature is reduced [2]. The low temperature electric behavior of $SrTiO_3$ approaches a ferroelectric phase transition; however, bulk $SrTiO_3$ is still paraelectric to the lowest temperature as a result of quantum fluctuations [3]. The 'quantum paraelectrics' or 'incipient ferroelectronics' of $SrTiO_3$ and other perovskite oxides have been a topic of considerable interest during the past few decades [3–5].

The ferroelectric transition of $SrTiO_3$ at low temperature can be induced by strains from lattice mismatch [5, 6], chemical [7, 8] or isotopic [9] substitution, electric field [10, 11], pressure [14] and controlled grain size [12]. Due to important applications in electronic devices, the coupling between strain and ferroelectricity in $SrTiO_3$ films has been intensively studied, and the relevant work is well illustrated in a recent review article [13]. By controlling the in-plane lattice strain, the critical temperature T_c of ferroelectric transition in thin film $SrTiO_3$ or superlattice can be profoundly enhanced [6, 14–18], even to room temperature [5]. However, the biaxial strains in thin films depend on the choice of substrate and film thickness, which turns out to be challenging for the synthesis of uniformly strained films because of the undesirable relaxation that occur when the thickness of a sample exceeds the

critical value. Room temperature ferroelectricity has also been reported for nonstoichiometric $SrTiO_3$ films with controlled Sr or O deficiencies [19, 22], though the mechanism is still under debate [15, 20, 21].

One fundamental property of ferroelectrics that changes quantitatively during phase transition is the dynamics of lattice vibration. The lattice dynamics of bulk $SrTiO_3$ has been studied theoretically and experimentally with neutron scattering techniques decades ago [22]. As a powerful tool to study the lattice properties, Raman scattering has been successfully used to detect the symmetry degeneration and phase transition in $SrTiO_3$. Since all the zone-center optical phonons of the ideal cubic $SrTiO_3$ are of odd parity, no first-order Raman scattering is expected to occur at ambient conditions. Instead, broad second-order peaks are observed in the wavelength ranges of 200–500 cm^{-1} and 550–750 cm^{-1}. Using an ultraviolet Raman spectroscopy technique, nanoscale ferroelectricity was successfully probed in ultrathin films of $BaTiO_3/SrTiO_3$ superlattice [23]. In the present work, we studied the response of ⟨001⟩-oriented $SrTiO_3$ single crystals to ion irradiation with Raman scattering and x-ray diffraction techniques. The appearance of forbidden optical phonon modes in the damaged regions suggests room temperature ferroelectricity in the ion-irradiated $SrTiO_3$. The strain depth profile in ion irradiated $SrTiO_3$ is quantitatively analyzed by single crystal x-ray diffraction measurements, and the results indicate a large tetragonal distortion with a significant out-of-plane lattice strain (1.1–1.3%) and negligible in-plane strain. The tetragonal distortion promotes the ferroelectric transition of ion irradiated $SrTiO_3$. The defects in the lattice induced by the energy transfer from Ti ions to the electronic structure also plays an important role for the ferroelectric transition in $SrTiO_3$ crystals.

2. Experimental procedure

The ⟨001⟩-oriented single crystals of $SrTiO_3$, with size of 12 × 15 mm^2, were irradiated at room temperature with 12 MeV or 20 MeV Ti ions to fluences from 1×10^{12} to 1×10^{14} cm^{-2}, with multiple irradiated areas of 3 × 3 mm^2 per sample. The ion irradiations were performed at several degrees off the surface normal to avoid channeling effects using the capabilities of the Ion Beam Materials Laboratory at the University of Tennessee [24]. The Raman spectra from the $SrTiO_3$ were collected in a reflection configuration using a high-resolution Raman spectrometer (LabRaman HR Evolution) at room temperature with a 532 nm green laser as the activation light. Irradiation-induced strain along the direction normal to the ⟨001⟩-oriented surface was measured with a high-resolution thin film x-ray diffractometer (PANalytical X'pert Pro) in 2θ–θ scan mode with Cu Kα1 x-ray radiation (λ = 1.5406 Å). The strain profiles for samples irradiated with 12 MeV Ti ions were derived from simulation of the XRD patterns with the program RaDMaX [25]. Reciprocal space maps were also recorded for the symmetric (002) and asymmetric (103) lattice planes of the samples irradiated with both 12 MeV and 20 MeV Ti ions, and the latter being used to determine the in-plane lattice strain.

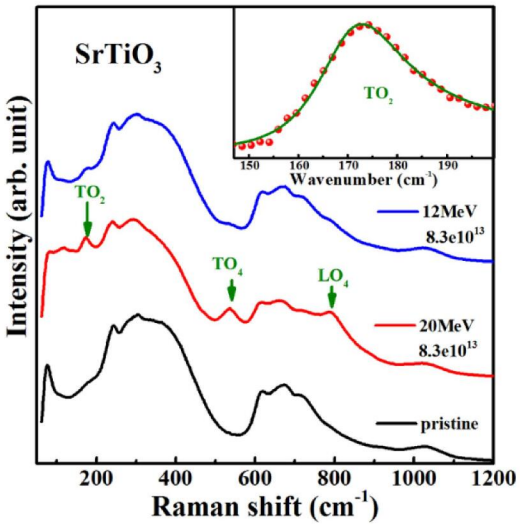


Figure 1. (a) The observed Raman spectrum of pristine $SrTiO_3$ and damaged with Ti ions of 12 MeV and 20 MeV in fluence of 8.3×10^{13} ions cm^{-2}. (b) The fitting of the Fano asymmetry Raman modes TO_2 and TO_4 for the 20 MeV Ti ions irradiated sample. The Fano fitting parameters are $A = 39.15$, $q = 4.11$, $\omega_0 = 170.2$ cm^{-1}, and $\Gamma = 21.98$ cm^{-1}.

3. Results and discussion

All the irradiated spots were characterized by Raman scattering measurements. There is only second-order Raman scattering signal in pristine $SrTiO_3$ because of the centrosymmetric structure. We observed additional Raman active modes in the irradiated samples, especially for the 20 MeV Ti ion irradiated spots. Figure 1 shows the Raman spectrum of $SrTiO_3$ irradiated with 12 MeV and 20 MeV Ti ions to a fluence of 8.3×10^{13} cm^{-2}, together with the spectrum from the pristine sample. The additional modes appearing in the sample irradiated with 20 MeV Ti ions are the polar transverse optic modes TO_2, TO_4 and polar longitudinal LO_4 modes, which are centered at ~170, 550 and 800 cm^{-1}, respectively. The appearance of these polar phonon modes in the irradiated samples is similar to the modes observed in ferroelectric films before [23, 26, 27], which is an indication of ferroelectricity. The corresponding phonon modes in the 12 MeV irradiated $SrTiO_3$ are weaker. In the 20 MeV Ti ion irradiated sample, there is a weak peak centered at ~140 cm^{-1}, which is the e_g mode of tetragonal $SrTiO_3$ [28]. Similar to the Raman spectrum of strained $SrTiO_3$ thin films, the appearance of the first-order Raman modes is due to breaking of the symmetry after ion irradiation. The ferroelectricity is caused by the polarization displacement of cations and anions in the damaged region. As observed in thin films [18] and nano-structured $SrTiO_3$ [12], a pronounced Fano asymmetric peak shape is seen for the TO_2 mode, which suggests coherent interference between the discrete phonon and a broad peak [29]. The Fano TO_2 mode in ion irradiated $SrTiO_3$ single crystal can also be fitted by the formula

$$I(\omega) = A\frac{[q + E(\omega)]^2}{1 + E(\omega)^2}$$

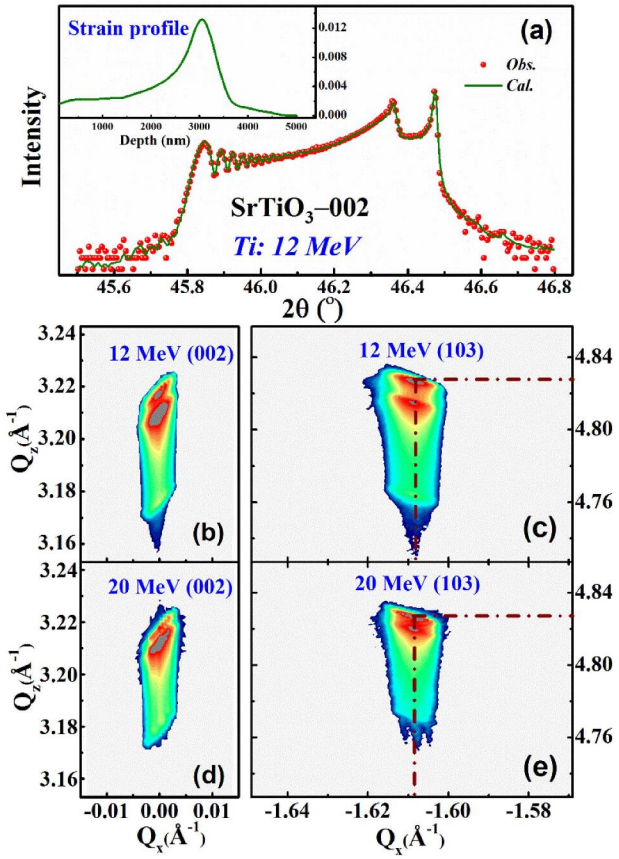


Figure 2. (a) The observed and calculated XRD profiles of the 12 MeV Ti ion irradiated $SrTiO_3$ around the Bragg peak (002). The maximum strain is ~1.32%, and the corresponding depth dependent strain profiles are shown as inserts; (b) and (c) the reciprocal space maps of 12 MeV Ti ion irradiated sample around the (002) and (103) Bragg peaks; (d) and (e) the reciprocal space maps of 20 MeV Ti ion irradiated $SrTiO_3$ near the lattice point of (002) and (103).

after subtracting a constant base line, where $E(\omega) = 2(\omega - \omega_0)/\Gamma$, and ω_0 is the phonon frequency, A is the amplitude, Γ is the full width at half maximum, and q is the asymmetry parameter. The fitting of TO_2 mode is shown as the insert of figure 1, and the phonon frequency is 170.2 cm^{-1}.

In order to measure the radiation-induced lattice strain, the samples were characterized using single crystal x-ray diffraction in a symmetric scan mode. Figure 2(a) shows the (002) Bragg peak of $SrTiO_3$ after 12 MeV Ti ion irradiation to a fluence of 8.3×10^{13} ions cm^{-2}. The x-ray beam penetrates the whole damaged layer, and the sharp peak in the high angle side is the Bragg peak from the undamaged part. The broad signal with lower 2θ angle comes from the damaged layers. The fringe features indicate the presence of a damage-induced dilation gradient in the direction normal to the sample surface [30]. The simulation of the diffraction pattern allows us to derive the depth-strain profile. As shown by the insert in figure 2(a), the derived strain profile yields a good fit to the measured XRD pattern. The maximum strain occurs at depth of ~3000 nm, which is in good agreement with the predicted damage profile based on SRIM calculations [31].The lattice expansion along $\langle 001 \rangle$ from ion irradiation has a maximum out-of-plan strain of 1.32%. Unlike thin films, it is usually observed that there is no in-plane strain for ion-irradiated crystals [32]. In order to determine the in-plane lattice strain, reciprocal space maps (RSMs) were measured for both the symmetric (002) and asymmetric (103) Bragg peak (figures 2(b) and (c)). The RSM of the asymmetric (103) peak shows only damage perpendicular to the sample surface. The scattering from both the damaged and undamaged region exhibit an identical value of Q_x coordinate which demonstrates that the lattice expansion parallel to the surface is negligible. The lattice strain can also be estimated from the RSMs. The maximum lattice strain for the sample irradiated with 12 MeV Ti ions is 1.31% and 1.30%, as estimated from the (002) and (103) RSMs, respectively. The maximum lattice strain estimated from RSMs is in good agreement with the one-dimensional XRD measurement. Similar measurements were performed for the sample irradiated with 20 MeV Ti ions. The XRD profile around the (002) Bragg peak shows the damage peak without well-resolved fringes which forbids a reliable simulation. The RSMs around (002) and (103) Bragg peaks are shown in figures 2(d) and (e), respectively. With a similar analysis, the maximum lattice strain in the sample irradiated with 20 MeV Ti ions is estimated to be 1.13% from both (002) and (103) RSMs. As shown in the depth dependent strain profile (figure 2(a)), ion irradiation induced damage is not homogeneous along the path of the ions and, near the sample surface, the out-of-plane lattice strain is relatively weak (<0.03%). It is thus important to check the structure in the whole damaged region. The maximum strain induced by 20 MeV Ti ion irradiation is slightly less than that for 12 MeV Ti ions, which indicates that the tetragonal distortion for 12 MeV Ti is larger than for 20 MeV Ti, at least in the maximum damaged region. However, the Raman spectrum (figure 1) clearly shows more ferroelectricity in the 20 MeV ion irradiated sample. This inconsistency suggested that symmetry breaking is not the only reason for the ferroelectric transition in ion irradiated $SrTiO_3$ crystals.

Figure 3(a) shows the depth dependent Raman spectrum from the $SrTiO_3$ sample irradiated with 20 MeV Ti ions over the whole damaged depth (<6 μm) with incremental depth measurement steps of 0.3 μm. The feature of ferroelectricity is clearly observed from the top to the maximum damaged depth (~3–4 μm). Beside the appearance of TO_2, TO_4 and LO_4 modes, the second-order Raman modes shift the center positions at different depths. As shown by the dashed guidelines in figure 3(a), the modes have red shifted gradually from surface to the maximum damaged depth of ~3.9 μm, then quickly switched back to higher wavenumber values, as in the pristine sample. This is an indication of the inhomogeneous lattice expansion with depth, and the maximum damaged region has the minimum wavenumber because of the maximum lattice expansion. The positions of the new phonon modes are not sensitive to depth or damage levels. After the Fano fit, however, the frequency of the TO_2 mode has undergone an observable shift (<2 cm^{-1}) due to the change of peak shape. In the maximum damaged region (2.4–3.3 μm), the peak position is nearly the same as the Fano fit (figure 3(b)). The symmetric TO_4 mode fitted with a Gaussian function shows no significant shift (<1 cm^{-1}) from surface to the maximum damaged

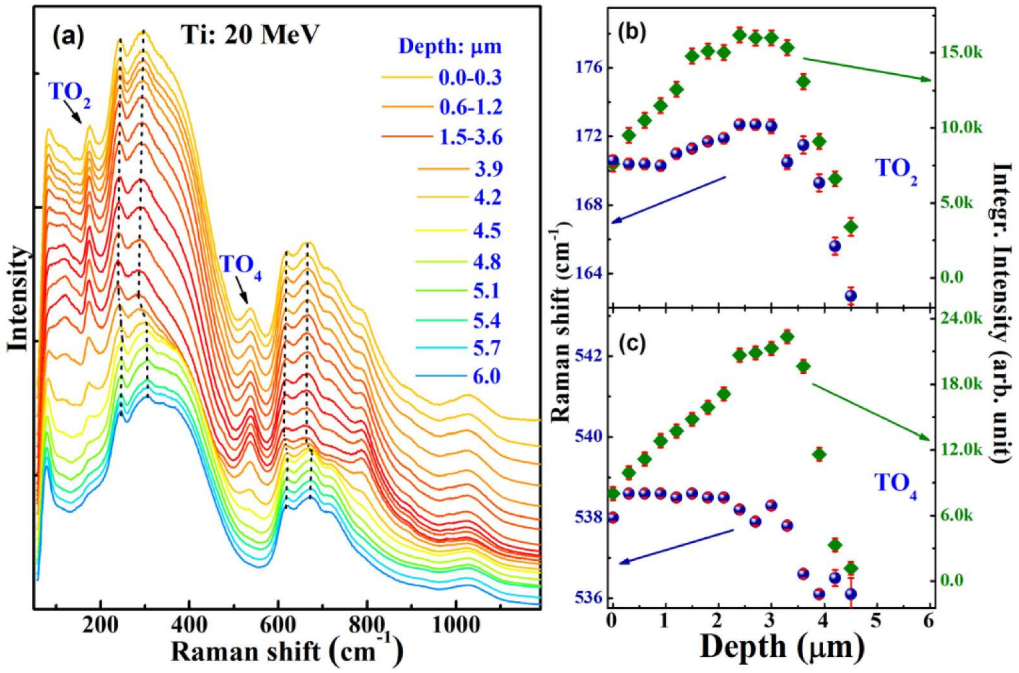


Figure 3. (a) The depth dependent Raman spectrum of $SrTiO_3$ irradiated with 20 MeV Ti ions. (b) and (c) The wavenumber and peak intensity of TO_2 mode with Fano asymmetry f tting and TO_4 mode with Gaussian f tting respectively.

region (f gure 3(c)). The intensity of both TO_2 and TO_4 modes increase with depth from the surface to the maximum damaged depth and then drops dramatically and eventually disappear. The cross-sectional Raman spectrum clearly indicates that the ferroelectricity starts from the very top surface to the maximum damaged region. The maximum damaged region has a tetragonal character, which can be seen from the weak tetragonal modes centered at 140 cm^{-1} and 478 cm^{-1}, respectively. After the maximum damage, the intensity of all the new modes dropped rapidly, this is consistent with the damage prediction by SRIM, as discussed later. The depth dependent Raman spectrum also suggests that symmetry degeneration in the maximum damaged region is not the only reason of the ferroelectric transition in $SrTiO_3$ crystal.

Raman spectrum (f gure 1) clearly indicates ferroelectric transition in $SrTiO_3$ is dependent on the ion energies, and the ferroelectric feature of 20 MeV Ti ion irradiated sample is more obvious than that in 12 MeV Ti ion irradiated samples. Figure 4 illustrates the energy deposition and damage levels (displacement per atom) for $SrTiO_3$ irradiated with 20 MeV and 12 MeV Ti ions at room temperature based on full-cascade SRIM calculations [33]. Except for the different ion penetration depths, the damage levels for 20 MeV and 12 Mev Ti ion irradiation of $SrTiO_3$ are similar (~0.05 dpa). The elastic energy loss to atomic nuclei in $SrTiO_3$ is very small (<0.1 keV nm^{-1}) in the f rst 1 μm region and <0.7 keV nm^{-1} in the maximum damage region. The much larger energy loss to the electrons is an inelastic process, and the effect on the lattice damage is not well understood [34]. Previous studies have shown that it has a complicated effect on the lattice, it can generate defects and, in the meanwhile, the strong electron–phonon coupling can also cause damage recovery, like

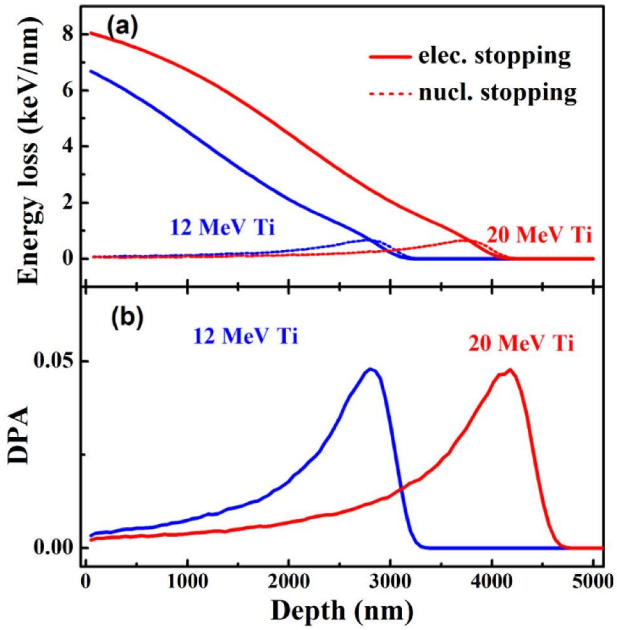


Figure 4. The calculated energy loss (a) and damage (b) in $SrTiO_3$ crystal irradiated with 12 MeV and 20 MeV Ti ions.

for MeV ions irradiated SiC [35]. A synergistic effect of electronic energy loss with pre-existing defects in $SrTiO_3$ has been conf rmed experimentally and theoretically [34, 36], and amorphous tracks and additional defects are generated in the predamaged crystal samples. High electron energy loss induces a localized thermal spike that can cause local melting of the sample along He ion path to form amorphous tracks via rapid quenching. The threshold in electron energy loss for forming

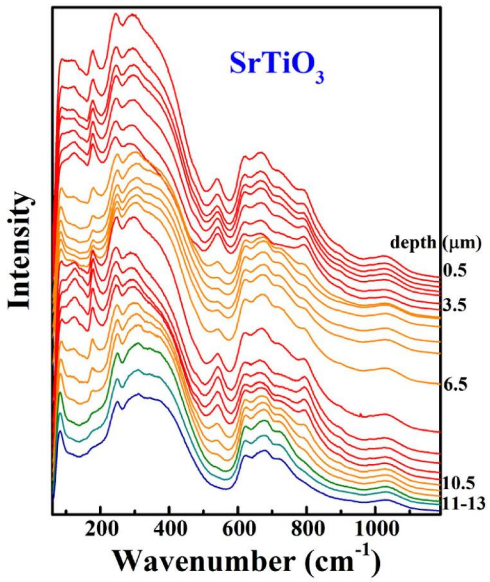


Figure 5. Cross section Raman spectrum of $SrTiO_3$ irradiated with 20 MeV Ti ions in fluence of 1×10^{14} cm^{-2}, and then measured with RBS, which the sample was bombard with 3.5 MeV He ions. The ferroelectricity layer has a thickness more than 10 μm, and the step of depth is 0.5 μm before 10.5 μm and 1 μm after 11 μm.

tracks in pristine $SrTiO_3$ is ~12.7 keV nm^{-1} [37]; however, in the case of slightly pre-damaged $SrTiO_3$, the threshold for amorphous track formation decreases significantly to about 6.5 keV nm^{-1} [36, 38]. While the electron energy loss of 12 MeV and 20 MeV Ti ions is less than the threshold for amorphous track formation in pristine $SrTiO_3$, their electronic energy loss is above the threshold for amorphous track formation in the presence of pre-existing defects. Thus, a delayed formation of amorphous tracks may occur once a sufficient concentration of defects accumulate due to nuclear collision processes, as has been observed in $LiTaO_3$ [39]. Since the electronic energy loss for 20 MeV Ti ions (figure 4(b)) is obviously higher than that for 12 MeV Ti ions, more damage production in the form of amorphous tracks and defects is expected for 20 MeV Ti ions. The damage due to the electronic energy loss may be directly related to the ferroelectric transition in $SrTiO_3$ crystals.

Room temperature ferroelectricity has been reported in non-stoichiometric $SrTiO_3$ thin films by controlling the oxygen deficiencies [19, 34]. Kim [20] has proposed the formation of a defect dipole by Sr–O–O clusters, which may be the possible origin of room temperature ferroelectricity in non-stoichiometric $SrTiO_3$ films. In addition to the tendency of a tetragonal structural transition, the room temperature ferroelectricity in $SrTiO_3$ due to Ti ion irradiation may have a similar origin, because oxygen vacancies can be easily generated by MeV ion irradiation. Previous photoluminescence and x-ray absorption measurements [41, 42] have suggested that ion irradiation of $SrTiO_3$ readily yields oxygen vacancy disorder and near-surface irradiation of $SrTiO_3$ with Ar ions also creates an oxygen deficiency [43].

Compared to thin film techniques, ion irradiation can make room temperature ferroelectricity in $SrTiO_3$ over much larger thicknesses. Figure 5 shows the depth dependent Raman spectrum from $SrTiO_3$ irradiated with 20 MeV Ti ions to a dose of 1×10^{14} cm^{-2}, and then subsequently irradiated with 3.5 MeV He ions for Rutherford backscattering spectroscopy measurements. The ferroelectricity is observed to a depth of ~10 μm. Two maxima in the damaged regions due to 20 MeV Ti ions and 3.5 MeV He ions irradiation are clearly seen from the Raman spectra. By irradiating with ions of high energies, such as swift heavy ions, it is expected that much thicker or even bulk $SrTiO_3$ can be transformed to ferroelectric state at room temperature.

4. Conclusions

Room temperature ferroelectricity was detected by Raman scattering in $SrTiO_3$ irradiated with Ti ions. X-ray diffraction measurements suggest that the transition is due to symmetry breaking, which caused by the large out-of-plane strains. $SrTiO_3$ irradiated with 20 MeV Ti ions shows more profound transition features than the sample irradiated with 12 MeV Ti ions. Ion irradiation induced damage, especially the formation of oxygen vacancies, may play an important role for the ferroelectric transition in $SrTiO_3$.

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