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# Symmetry degeneration and room temperature ferroelectricity in ion irradiated SrTiO<sub>3</sub>

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## Abstract

Polar phonon modes associated with room temperature ferroelectricity are observed in SrTiO<sub>3</sub> single crystals irradiated with Ti ions. Quantitative strain analysis reveals that irradiation-induced out-of-plane strain drives the centrosymmetric cubic SrTiO<sub>3</sub> to a tetragonal-like structure in the maximum damaged region. Energy transfer from ions to electrons during ion irradiation yields defects in SrTiO<sub>3</sub> that also plays an important role for the room temperature ferroelectricity. Different from thin film techniques, the ferroelectricity in the ion irradiated SrTiO<sub>3</sub> can occur for much larger thicknesses, depending on the energy and type of ion.

## 1 Introduction

Bulk SrTiO<sub>3</sub> 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<sub>3</sub> deviates from the classical Curie–Weiss law at low temperature, and it increases rapidly (up to  $1.8 \times 10^4$  at 1.4 K) as the temperature is reduced [2]. The low temperature electric behavior of SrTiO<sub>3</sub> approaches a ferroelectric phase transition; however, bulk SrTiO<sub>3</sub> is still paraelectric to the lowest temperature as a result of quantum fluctuations [3]. The ‘quantum paraelectrics’ or ‘incipient ferroelectrics’ of SrTiO<sub>3</sub> and other perovskite oxides have been a topic of considerable interest during the past few decades [3–5].

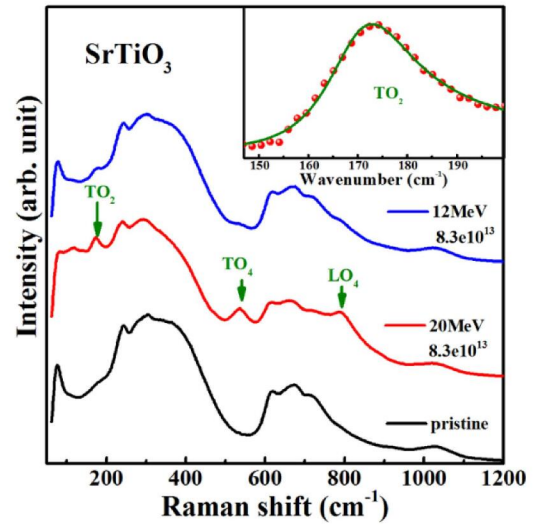
The ferroelectric transition of SrTiO<sub>3</sub> at low temperature can be induced by strains from lattice mismatch [5, 6], chemical [7, 8] or isotopic [9] substitution, electric field [10, 11], pressure [14] and controlled grain size [12]. Due to important applications in electronic devices, the coupling between strain and ferroelectricity in SrTiO<sub>3</sub> 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<sub>3</sub> 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<sub>3</sub> 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<sub>3</sub> 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<sub>3</sub>. Since all the zone-center optical phonons of the ideal cubic SrTiO<sub>3</sub> 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<sup>-1</sup> and 550–750 cm<sup>-1</sup>. Using an ultraviolet Raman spectroscopy technique, nanoscale ferroelectricity was successfully probed in ultrathin films of BaTiO<sub>3</sub>/SrTiO<sub>3</sub> superlattice [23]. In the present work, we studied the response of  $\bar{1}001$ -oriented SrTiO<sub>3</sub> 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<sub>3</sub>. The strain depth profile in ion irradiated SrTiO<sub>3</sub> 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<sub>3</sub>. 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<sub>3</sub> crystals.

## 2. Experimental procedure

The  $\bar{1}001$ -oriented single crystals of SrTiO<sub>3</sub>, with size of 12 × 15 mm<sup>2</sup>, were irradiated at room temperature with 12 MeV or 20 MeV Ti ions to fluences from 1 × 10<sup>12</sup> to 1 × 10<sup>14</sup> cm<sup>-2</sup>, with multiple irradiated areas of 3 × 3 mm<sup>2</sup> 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<sub>3</sub> 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  $\bar{1}001$ -oriented surface was measured with a high-resolution thin film x-ray diffractometer (PANalytical X'pert Pro) in 2 $\theta$ - $\theta$  scan mode with Cu K $\alpha$ 1 x-ray radiation ( $\lambda = 1.5406$  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.

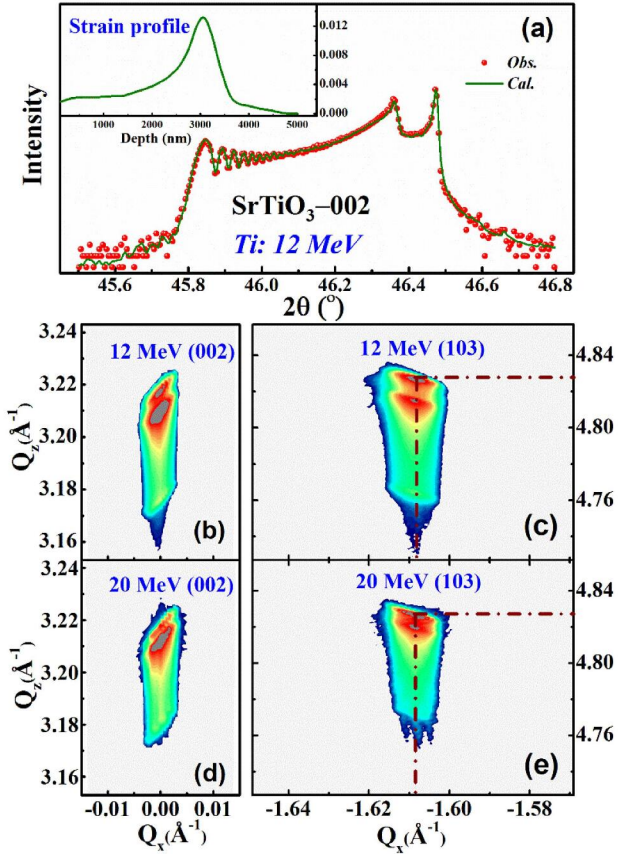


**Figure 1.** (a) The observed Raman spectrum of pristine SrTiO<sub>3</sub> and damaged with Ti ions of 12 MeV and 20 MeV in fluence of  $8.3 \times 10^{13}$  ions cm<sup>-2</sup>. (b) The fitting of the Fano asymmetric Raman modes TO<sub>2</sub> and TO<sub>4</sub> for the 20 MeV Ti ions irradiated sample. The Fano fitting parameters are  $A = 39.15$ ,  $q = 4.11$ ,  $\omega_0 = 170.2$  cm<sup>-1</sup>, and  $\Gamma = 21.98$  cm<sup>-1</sup>.

## 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<sub>3</sub> 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<sub>3</sub> irradiated with 12 MeV and 20 MeV Ti ions to a fluence of  $8.3 \times 10^{13}$  cm<sup>-2</sup>, 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<sub>2</sub>, TO<sub>4</sub> and polar longitudinal LO<sub>4</sub> modes, which are centered at ~170, 550 and 800 cm<sup>-1</sup>, 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<sub>3</sub> are weaker. In the 20 MeV Ti ion irradiated sample, there is a weak peak centered at ~140 cm<sup>-1</sup>, which is the e<sub>g</sub> mode of tetragonal SrTiO<sub>3</sub> [28]. Similar to the Raman spectrum of strained SrTiO<sub>3</sub> 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<sub>3</sub> [12], a pronounced Fano asymmetric peak shape is seen for the TO<sub>2</sub> mode, which suggests coherent interference between the discrete phonon and a broad peak [29]. The Fano TO<sub>2</sub> mode in ion irradiated SrTiO<sub>3</sub> single crystal can also be fitted by the formula

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



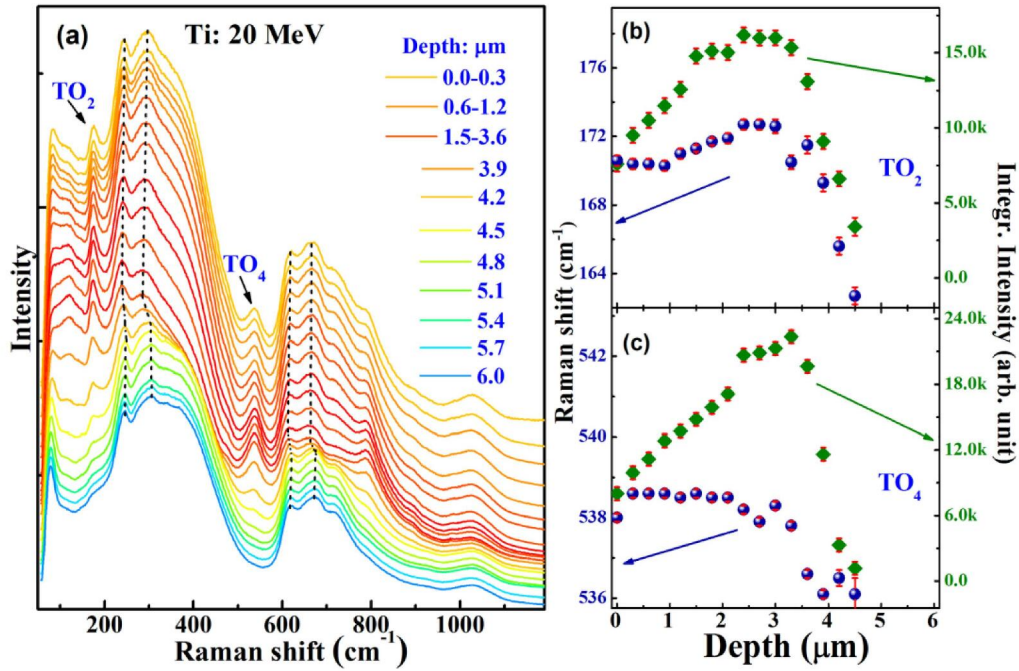
**Figure 2.** (a) The observed and calculated XRD profiles of the 12 MeV Ti ion irradiated SrTiO<sub>3</sub> around the Bragg peak (002). The maximum strain is  $\sim 1.32\%$ , and the corresponding depth dependent strain profiles are shown as inserts; (b) and (c) the reciprocal space maps of 12 MeV 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<sub>3</sub> near the lattice point of (002) and (103).

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

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<sub>3</sub> after 12 MeV Ti ion irradiation to a fluence of  $8.3 \times 10^{13} \text{ ions cm}^{-2}$ . 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  $2\theta$  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  $\sim 3000 \text{ nm}$ , which is in good agreement with the predicted damage profile based on SRIM calculations [31]. The lattice expansion along  $h001i$  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<sub>3</sub> crystals.

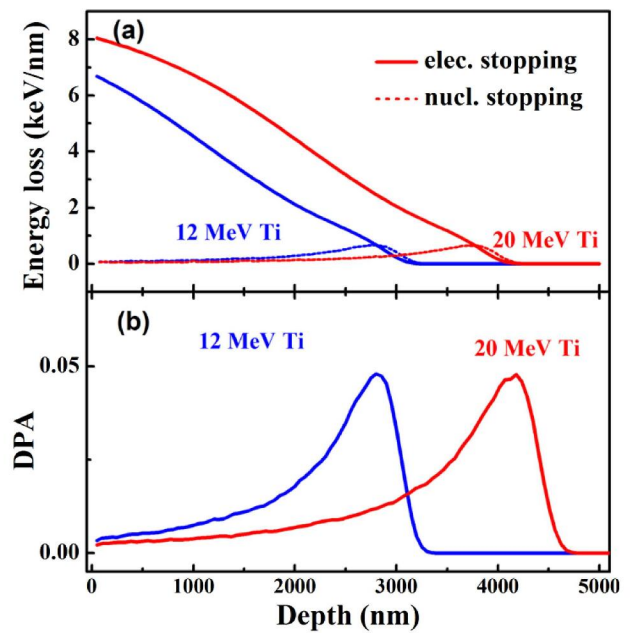
Figure 3(a) shows the depth dependent Raman spectrum from the SrTiO<sub>3</sub> sample irradiated with 20 MeV Ti ions over the whole damaged depth ( $<6 \mu\text{m}$ ) with incremental depth measurement steps of  $0.3 \mu\text{m}$ . The feature of ferroelectricity is clearly observed from the top to the maximum damaged depth ( $\sim 3\text{--}4 \mu\text{m}$ ). Beside the appearance of TO<sub>2</sub>, TO<sub>4</sub> and LO<sub>4</sub> 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  $\sim 3.9 \mu\text{m}$ , 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<sub>2</sub> mode has undergone an observable shift ( $<2 \text{ cm}^{-1}$ ) due to the change of peak shape. In the maximum damaged region ( $2.4\text{--}3.3 \mu\text{m}$ ), the peak position is nearly the same as the Fano fit (figure 3(b)). The symmetric TO<sub>4</sub> mode fitted with a Gaussian function shows no significant shift ( $<1 \text{ cm}^{-1}$ ) from surface to the maximum damaged



**Figure 3.** (a) The depth dependent Raman spectrum of SrTiO<sub>3</sub> irradiated with 20 MeV Ti ions. (b) and (c) The wavenumber and peak intensity of TO<sub>2</sub> mode with Fano asymmetry fitting and TO<sub>4</sub> mode with Gaussian fitting respectively.

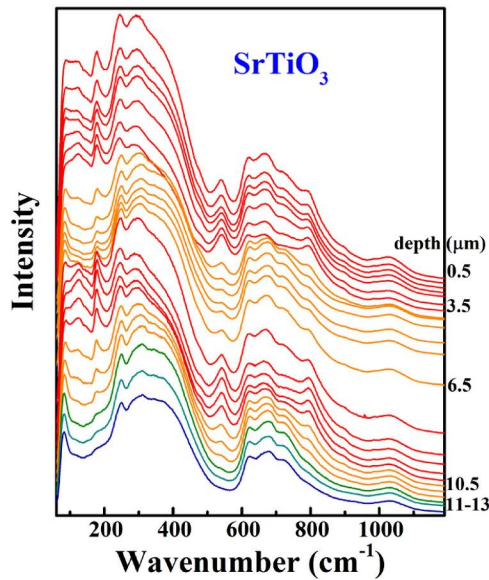
region (figure 3(c)). The intensity of both TO<sub>2</sub> and TO<sub>4</sub> modes increase with depth from the surface to the maximum damaged depth and then drops dramatically and eventually disappear. The cross-sectional Raman spectrum clearly indicates that the ferroelectricity starts from the very 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<sup>-1</sup> and 478 cm<sup>-1</sup>, 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<sub>3</sub> crystal.

Raman spectrum (figure 1) clearly indicates ferroelectric transition in SrTiO<sub>3</sub> 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<sub>3</sub> 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<sub>3</sub> are similar (~0.05 dpa). The elastic energy loss to atomic nuclei in SrTiO<sub>3</sub> is very small (<0.1 keV nm<sup>-1</sup>) in the first 1 μm region and <0.7 keV nm<sup>-1</sup> 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<sub>3</sub> 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<sub>3</sub> has been confirmed experimentally and theoretically [34, 36], and amorphous tracks and additional defects are generated in the pre-damaged 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<sub>3</sub> irradiated with 20 MeV Ti ions in f uence of  $1 \times 10^{14} \text{ cm}^{-2}$ , and then measured with RBS, which the sample was bombard with 3.5 MeV He ions. The ferroelectric layer has a thickness more than 10  $\mu\text{m}$ , and the step of depth is 0.5  $\mu\text{m}$  before 10.5  $\mu\text{m}$  and 1  $\mu\text{m}$  after 11  $\mu\text{m}$ .

tracks in pristine SrTiO<sub>3</sub> is  $\sim 12.7 \text{ keV nm}^{-1}$  [37]; however, in the case of slightly pre-damaged SrTiO<sub>3</sub>, the threshold for amorphous track formation decreases significantly to about 6.5  $\text{keV nm}^{-1}$  [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<sub>3</sub>, 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<sub>3</sub> [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<sub>3</sub> crystals.

Room temperature ferroelectricity has been reported in non-stoichiometric SrTiO<sub>3</sub> 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<sub>3</sub> films. In addition to the tendency of a tetragonal structural transition, the room temperature ferroelectricity in SrTiO<sub>3</sub> 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<sub>3</sub> readily yields oxygen vacancy disorder and near-surface irradiation of SrTiO<sub>3</sub> with Ar ions also creates an oxygen deficiency [43].

Compared to thin film techniques, ion irradiation can make room temperature ferroelectricity in SrTiO<sub>3</sub> over much larger

thicknesses. Figure 5 shows the depth dependent Raman spectrum from SrTiO<sub>3</sub> irradiated with 20 MeV Ti ions to a dose of  $1 \times 10^{14} \text{ cm}^{-2}$ , and then subsequently irradiated with 3.5 MeV He ions for Rutherford backscattering spectroscopy measurements. The ferroelectricity is observed to a depth of  $\sim 10 \mu\text{m}$ . 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<sub>3</sub> can be transformed to ferroelectric state at room temperature.

## 4. Conclusions

Room temperature ferroelectricity was detected by Raman scattering in SrTiO<sub>3</sub> 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<sub>3</sub> 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<sub>3</sub>.

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