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Optical strain sensing for free-standing membrane energy harvesting devices
環境発電デバイスへ向けたフリースタンディング薄膜における ひずみの光学的計測

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1. Introduction

Low-power energy harvesting is a technique where energy is collected from the environment for the purpose of providing a power supply for distributed electronic applications, such as environmental sensors. This work is related to developing piezoelectric thin film devices for collecting vibrational energy from the environment and converting the mechanical energy to electricity. For low-frequency vibrational energy conversion, dynamic bending stress is applied on a flexible piezoelectric material [1]. However, only limited stress can be applied on ceramic piezoelectric thin films due to the presence of a rigid substrate that cracks long before the strain limit of the piezoelectric film itself is reached. This problem can be solved by constructing free-standing flexible devices that are detached from a crystalline substrate after film growth. In practice, high-quality thin films can be grown on a crystalline substrate and then transferred from the rigid single-crystal substrate to a flexible carrier. The motivation of my study is to develop a thin film fabrication process for free-standing $BaTiO_3$ piezoelectric films and develop e technique for analyzing the strain distribution in such devices during mechanical deformation.

Measuring the magnitude of local strain is an important issue in designing an energy harvesting device. For maximum efficiency, strain in a membrane device should be uniformly distributed. In commonly used cantilever devices, however, strain is inhomogeneous and may lead to film fracture at high-strain points. Optical analysis of the surface deformation is one possibility but may not be useful for films where strain relaxation may occur at grain boundaries and the average surface profile does not give a good estimate of true local strain. An internal strain detector would thus be more useful for analyzing the performance of a flexible energy conversion device. One possible solution is to coat a piezoelectric film with a VO_2 layer. VO_2 has a metal-insulator transition (MIT) that is conveniently close to room temperature and the transition is strongly affected by strain [2]. The change from insulating to metallic state can be detected by measuring near infrared reflectivity with a camera [3]. The local reflectivity change of a VO_2 film can thus be used to measure the local microscopic strain distribution in a macroscopic device.

The purpose of this work was thus to develop free-standing piezoelectric oxide thin films and to attempt to detect local strain changes by observing the infrared reflectivity of VO_2 overlayers.

2. Experiment

2.1 Free-standing $BaTiO_3$ thin films

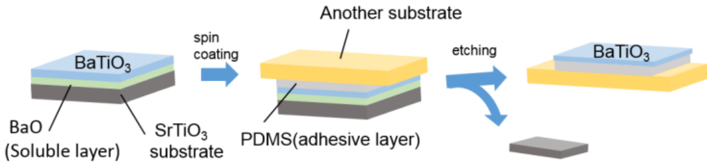

Fig. 1 Process of making a free-standing $BaTiO_3$ membrane.

High-quality piezoelectric oxide films need to be grown on single-crystal substrates, but to get a free-standing film, it also needs to be separated from the substrate. To do this (Fig. 1), an epitaxial BaO buffer layer was grown by Pulsed Laser Deposition (PLD) on a $SrTiO_3$ substrate using a KrF excimer laser at 400°C and 10^{-6} Torr of oxygen. An epitaxial $BaTiO_3$ film was then grown on the BaO buffer layer at 600°C and 10^{-5} Torr. The thin film was then attached to a plastic substrate with a polymer binder and the original single crystal $SrTiO_3$ substrate was released by etching away the water-soluble BaO layer. A flexible high-quality oxide membrane can thus be produced.

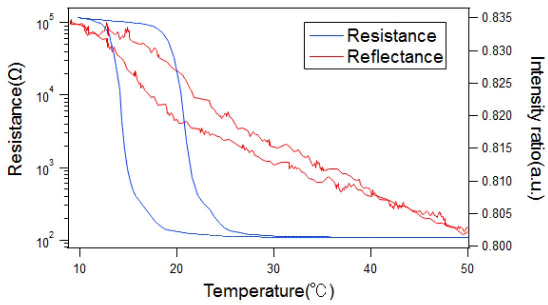

Fig. 2 Resistance and reflectance change of 10 nm VO_2 film during MIT.

2.2 VO_2 thin film growth

VO_2 thin films were grown by PLD on TiO_2 substrates using a KrF excimer laser at 380°C and 4.4 mTorr of oxygen. The films were characterized by X-ray diffraction (XRD) and atomic force microscopy (AFM). The resistance of the films was measured by the four-probe method. Fig. 2 shows the temperature dependence of resistance and reflectance of a 10 nm thick VO_2 film on a 0.5 mm TiO_2 substrate. A reflectance change can be obtained in this sample along with the MIT which is caused by the temperature change. For bending measurement, a 0.5 mm thick substrate is too thick, so VO_2 films were also grown on 0.2 mm thick TiO_2 substrates. The film growth conditions have to be optimized for each substrate type. Fig. 3 shows an example of growth temperature optimization. In this series of samples, the oxygen pressure and film thickness were fixed to 4.4 mTorr and 10 nm. The XRD measurement shows that a sample grown at a lower temperature has a shorter *c*-axis lattice parameter, indicating that there is a stronger epitaxial strain from the substrate. The sample with the highest epitaxial strain shows the lowest transition temperature and the sharpest MIT in the resistance measurement. This sample was used in the bending strain measurement because the phase transition occurs over a very narrow temperature range and the sensitivity to small additional strain can be expected to be high.

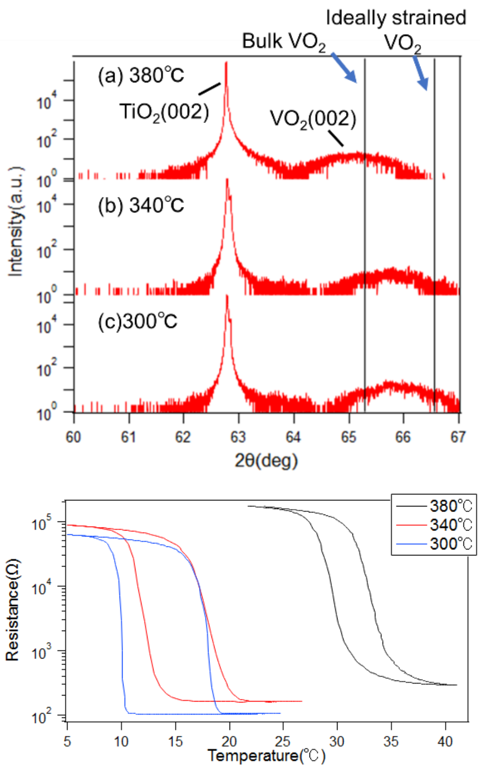

Fig. 3 Results of resistance and XRD measurement of VO_2 sample grown at various temperatures.

2.3 Sensing local strain in thin films

In this study, a new measurement setup was developed for applying uniaxial strain on a thin film sample by bending the substrate [4]. Fig. 4 shows the schematic of this bending stage. Substrates deformed in three-point geometry by applying controlled force with a piezo actuator at the center of the substrate. A thermistor is attached near the sample and the temperature can be controlled with two Peltier devices. The resistance and reflectance can be measured while bending.

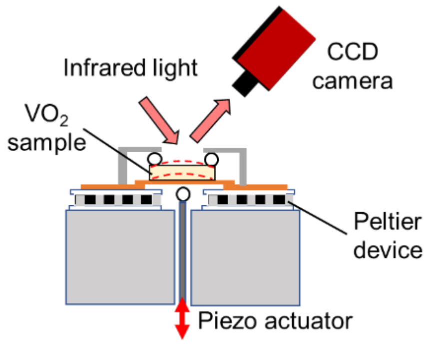

Fig. 4 Diagram of the bending stage.

3. Results and discussion

Fig. 5 shows the results of resistance and reflectance measurement while applying stress on the sample on the bending stage. During measurement, the temperature was fixed close to the MIT midpoint at 15 °C. A slight temperature drift causes the slow resistance increase. The arrows in the figure mark periods when static stress was applied to the VO_2 film. The strain level was increased by applying higher voltages to the piezo actuator. The resistance and reflectance decreased under static strain and the amount of change was proportional to the magnitude of the strain. Since the MIT temperature is strain dependent, when measuring resistance or reflectivity at a fixed temperature, any additional bending strain will further shift the MIT, and thus an additional fraction of the sample will switch from insulating to metallic state, decreasing resistance and reflectance.

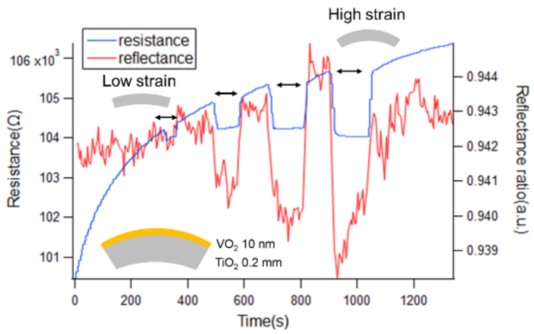

Fig. 5 Resistance and reflectance measurement of a VO_2 thin film during repeated bending.

4. Conclusion

High-quality $BaTiO_3$ thin films were grown on $SrTiO_3$ substrates and successfully transferred to a plastic carrier. For the purpose of optical strain sensing, VO_2 films with a sharp MIT near room temperature were grown on TiO_2. The reflectance change of a VO_2 thin film could be observed when bending the sample. This result shows that the near-infrared reflectance of a VO_2 thin film is determined by the internal strain and can thus be used as an internal strain sensor for spatial strain mapping in flexible devices.

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Presentation list

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